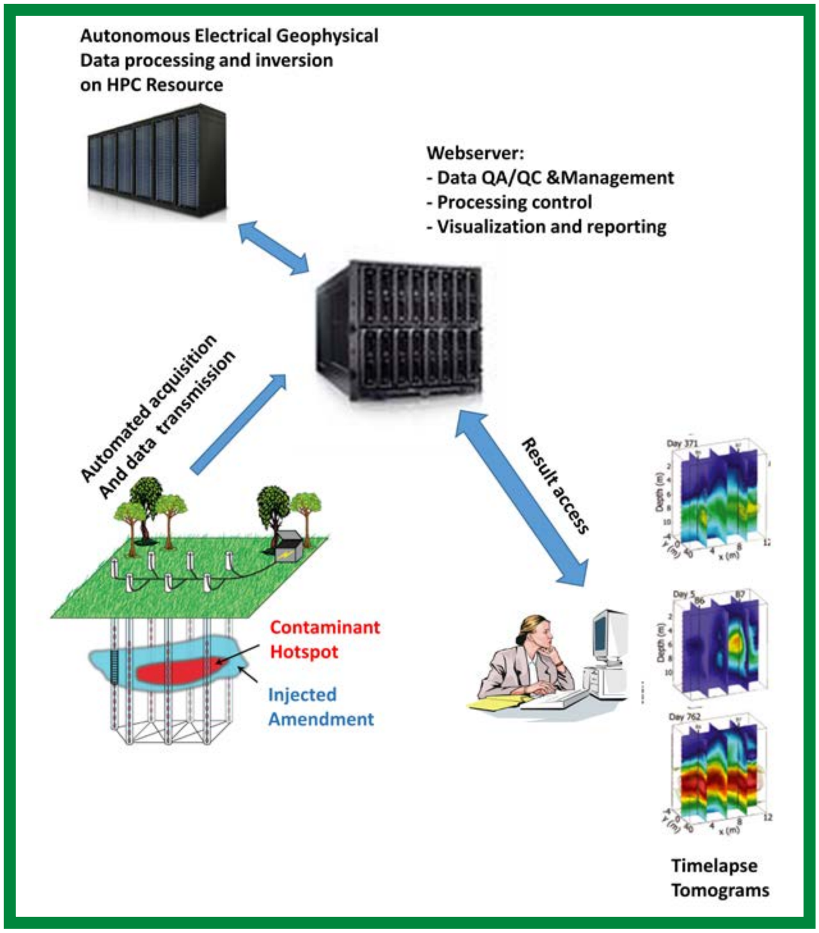
ESTCP
Cost and Performance Report

(ER-200717)



Optimized Enhanced Bioremediation Through 4D Geophysical Monitoring and Autonomous Data Collection, Processing and Analysis

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ACRONYMS AND ABBREVIATIONS

3D	three dimensional
4D	four dimensional
ABC®	Anaerobic BioChem
AFB	Air Force Base
bgs	below ground surface
BGS	British Geological Survey
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CPU	central processing unit
DCE	dichloroethene
DNAPL	Dense Non Aqueous Phase Liquid
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRMO	Defense Reutilization and Marketing Office
DSA	Defense Supply Agency
EC2	Elastic compute cloud
ERT	electrical resistivity tomography
ESTCP	Environmental Security Technology Certification Program
GPR	ground penetrating radar
HPC	High-Performance computing
HPMS	Hydrogeophysical Performance Monitoring System
HRC®	Hydrogen Release Compound
μg/L	micrograms per liter
MCL	Maximum Contaminant Level
mg/L	milligrams per liter
MPI	Message Passing Interface
%	percent
PCE	tetrachloroethene
PI	Principal Investigator
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RI	remedial investigation
RPM	Remedial Project Managers

TCE	trichloroethene
USEPA	U.S. Environmental Protection Agency
USGS	United States Geological Survey
VC	vinyl chloride
VOC	volatile organic compound

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EXECUTIVE SUMMARY

Enhanced in situ bioremediation has become widely used, because it is relatively inexpensive and effective, as long as it is implemented appropriately. One of the major limitations to the effectiveness of in situ bioremediation is that performance is dependent on effective amendment delivery, and yet practitioners generally have little knowledge of the subsurface distribution of amendments. As a result, there is often substantial uncertainty about whether treatment design criteria have been met, or if (and where and when) additional injections are required. Such uncertainty is either addressed through dense sampling, or through overly conservative remedial efforts, both of which are costly.

This project demonstrated the use of geophysical techniques to provide near real-time information on the spatial and temporal distribution of amendments noninvasively and cost effectively. The technology uses electrical resistivity measurements from a series of wells to detect changes in electrical conductivity. electrical resistivity monitoring is particularly useful for enhanced bioremediation because the amendment solutions used for bioremediation increase the bulk electrical conductivity significantly above the background conductivity. Time-lapse electrical resistivity monitoring can delineate where amendments were initially delivered, as well as track their migration and depletion over time. Near real-time information is particularly valuable because it can allow modifications and/or additional injections while equipment is still present on site.

The system demonstrated in this project is referred to as the Hydrogeophysical Performance Monitoring System (HPMS). The HPMS consists of commercially available hardware and custom designed software for data collection, data transfer, data processing and web-based result visualization. Two demonstrations of the HPMS were performed at the Brandywine Defense Reutilization and Marketing Office (DRMO) site in Brandywine, Maryland. The first demonstration, which lasted from March 2008 until the summer of 2010, involved injection of a proprietary lactate amendment (Anaerobic BioChem [ABC®]). The second demonstration, in August 2010, involved monitoring two injections of molasses, and showcased the delivery of near real-time results to project team members and program managers in the field.

Both demonstrations successfully demonstrated the ability of electrical geophysical monitoring to provide near real-time, actionable information on the spatial and temporal behavior of amendments, for considerably less cost than invasive sampling. The estimated cost of the HPMS system was roughly half the cost of invasive sampling, while providing more complete and timely information on the amendment distribution. The longer demonstration also showed that electrical geophysical monitoring can provide information on the biogeochemical changes associated with in situ bioremediation, while the shorter demonstration proved the system can provide stakeholders with actionable information on amendment behavior within 30 minutes after injection.

1.0 INTRODUCTION

1.1 BACKGROUND

Thousands of U.S. Department of Defense (DoD) sites have contaminated soil and groundwater, resulting from a range of different operations related activities. As of 2005 the DoD had invested $20 billion in the environmental restoration of contaminated sites, and the cleanup of contaminated groundwater remains one of the largest environmental liabilities of DoD (GAO, 2005).

In-situ remedial efforts such as enhanced bioremediation have shown to be successful in accelerating cleanup of recalcitrant compounds. Due to the potential for cost savings of in-situ techniques compared to ex-situ techniques, such as pump-and-treat, there is substantial interest from DoD in enhanced bioremediation (Parsons, 2004) which is now being proposed as an integral part of remedial solutions at multiple DoD sites.

Enhanced bioremediation involves the addition of microorganisms and/or nutrients to the subsurface environment to accelerate the natural biodegradation process. One of the most common bioremediation methods is the injection of organic liquid nutrients such as lactate, molasses, Hydrogen Release Compound (HRC®), and vegetable oils.

Multiple laboratory and field studies have resulted in a detailed understanding of the behavior of different liquid nutrient amendments and the expected microbial processes. These studies have led to regulatory acceptance of bioremediation as a remedial strategy, and as a result of this acceptance enhanced bioremediation services are now being offered by multiple commercial providers.

In the typical remedial scenario amendment is emplaced via injection throughout the contaminated zone. Such injections can be coupled with permeability or pH enhancements. Knowledge of amendment distribution is generally obtained from model based assumptions and sparse and expensive groundwater sampling efforts. Consequently, there is substantial uncertainty on whether injection design criteria have been met, or where additional injections may be required to achieve or maintain amendment concentrations required for optimal efficiency. Such uncertainty is either resolved through sampling, or is addressed through overly conservative remedial efforts, both of which negatively impact the cost and efficiency of remedial effort.

The problem of how to reduce the uncertainty in amendment emplacement knowledge is addressed by this effort.

Time-lapse electrical resistivity measurements have been demonstrated to be capable of mapping spatial and temporal changes in subsurface electrical conductivity (Versteeg et al., 2000; Slater et al., 2002; Williams et al., 2005; Davis et al., 2006). Amendments used in bioremediation typically have an electrical conductivity that substantially differs from bulk background subsurface electrical conductivity. Amendments are typically injected in substantial volumes per injection point, and thus the injection of amendments will result in a substantial change in subsurface conductivities.

After injection, the amendment will typically move (due to groundwater gradients). In addition, changes in conductivities of both the liquid and solid phases will occur due to different geochemical processes. Thus, in theory both the initial injection and subsequent movement and changes in amendment properties can be mapped through time-lapse electrical measurements to provide spatial and volumetric information about amendment behavior.

The feasibility of doing this automatically and autonomously to provide near real time information on amendment behavior was demonstrated under this effort. This approach has multiple advantages compared to current approaches (Table 1). Including:

- ***Volumetric information versus point information:*** the approach demonstrated here provided information on amendment behavior in three dimensional (3D), whereas traditional methods only provide information on amendment behavior at discrete sampling points.
- ***Dense versus sparse temporal information:*** the demonstrated approach provides (dependent on configuration of the system) information on amendment behavior on an hourly or daily basis.
- ***Reduction in overall cost:*** while sampling and analysis costs are recurring costs, our system mainly requires an upfront installation cost, with components that can be reused between different sites. Furthermore, geophysical data can be used to reduce the frequency of sampling or trigger more cost-effective sampling when subsurface changes are occurring.

Table 1. Comparison of time lapse resistivity against sampling based approaches.

Sampling Based Approaches	Time Lapse Resistivity
Spatial Density of Information	
Only point data	Volumetric information
Temporal Information	
Typically quarterly	Hourly to daily
Cost	
Sampling and analysis costs continue during project	Mainly up front installation cost

With the technology described here, far fewer wells will be required for understanding amendment distributions, leading to significant cost savings (20 to 50% or greater per site) due to fewer monitoring requirements (e.g., wells, samples, lab analyses) and more optimized remedial applications based on rapid identification of missed target zones. This should lead to substantial cost savings over the life of the remedial effort.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstration was to validate and demonstrate the use of autonomous time-lapse electrical resistivity as an effective amendment monitoring tool. This was done through a field based demonstration at the Brandywine Defense Reutilization and Marketing Office (DRMO). This demonstration had two parts: a one and a half year monitoring effort of the spatial and temporal evolution of a lactate based amendment which was injected as part of an ongoing

bioremediation effort at the Brandywine DRMO, and a short-term monitoring effort of two molasses injections at the same site in August 2010. Real time monitoring of the two latter injections (in tandem with the actual amendment emplacement) was demonstrated to DoD and U.S. Department of Energy (DOE) scientists both in person and through a live webcast.

1.3 REGULATORY DRIVERS

The U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) in drinking water are 5 micrograms per liter (µg/L) for tetrachloroethene (PCE) and trichloroethene (TCE), and 70 µg/L for *cis*-dichloroethene (DCE), and 2 µg/L for vinyl chloride (VC). Concentrations of PCE, TCE, *cis*-DCE and VC exceed these MCLs at a significant number of DoD sites. The use of amendment injection for enhanced bioremediation of chlorinated solvents is one of the primary methods used by DoD to bring these sites into compliance with federal, state, and local regulations. Use of four dimensional (4D) geophysical methods to verify amendment distribution and the remedial process within specific contamination zones provides site stakeholders with quantitative data which support the assessment of remedial progress and functioning.

This project also addressed several high priority needs from the Navy Environmental Quality, Research, Development, Testing/Evaluation Requirements including:

- 1.I.01.g Improved Remediation of Groundwater Contaminated with Halogenated Hydrocarbons and Other Organics;
- 1.III.02.a Remote Sensing for Site Characterization and Monitoring;

Additionally, the following DoD needs from the Air Force Assessment Survey (NAS) are also addressed:

- 100-130.01 Effective Dense Non-Aqueous Phase Liquid (DNAPL) Characterization, Monitoring and Detection Technology; 100-131 Improved Remediation Monitoring Technologies;
- 500-570 Improve Understanding of DNAPL Groundwater Transport to Accurately Predict Fate of Contaminants

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2.0 TECHNOLOGY

The technology, termed the Hydrogeophysical Performance Monitoring System (HPMS), couples automatic and autonomous electrical geophysical monitoring with automated data processing and result delivery. The elements of this system are shown in Figure 1 and discussed in the following section. It should be noted that electrical resistivity monitoring (and the use of resistivity monitoring for long term process studies) is done by numerous other groups. The system described here bears resemblance to different systems, including most recently the system developed and demonstrated by the British Geological Survey (BGS) (Ogilvy et al., 2009). However, while the concept of resistivity monitoring is well established and many groups have demonstrated aspects of the systems (most commonly remote data retrieval from field systems), apart from the BGS system the project team is unaware of any other field demonstrations of **fully automated** systems.

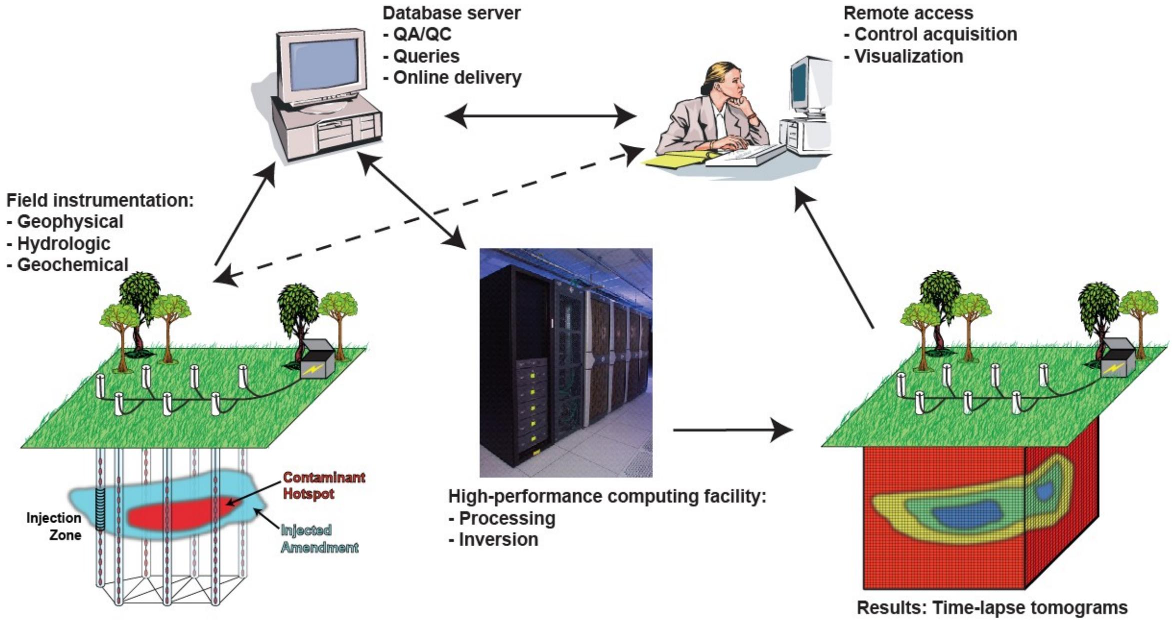

Figure 1. Schematic of the HPMS.

Data is collected in the field, and transmitted to a server for quality assurance (QA)/quality control (QC) and parsing in a relational database. Processing and inversion is done on a High-Performance Computing (HPC) cluster. Results (including time lapse tomograms) are accessible to end-users through a browser interface.

2.1 TECHNOLOGY DESCRIPTION

This demonstration/evaluation project capitalized on previous developments documented in geophysical literature. The project team relied heavily on existing hardware for acquisition of time-lapse electrical data, as well as on research and development by the project team members and others on time-lapse monitoring of natural and engineered hydrologic processes. In this section (Section 2.1) the state of geophysical monitoring methods is reviewed and the relevance of various methods to monitoring bioremediation is discussed. In subsequent sections, we focus

on developments made under this Environmental Security Technology Certification Program (ESTCP) project.

2.1.1 Time-lapse Geophysics

Geophysical methods are a standard tool for obtaining information on volumetric distributions of subsurface physical properties of rocks and fluids. One can distinguish primary physical properties (those which appear in the equations describing the physics of each method) and the inferred properties. The inferred properties are typically obtained through a petrophysical relationship, such as Archie's law (Archie, 1942) which relates the electrical conductivity of a sedimentary rock to its porosity and brine saturation. Such petrophysical relationships are generally obtained experimentally through laboratory or field measurements. However, efforts are underway to develop such relationships from fundamental material properties. A range of geophysical methods exist (Table 2) each of which can provide information on different primary physical and inferred properties.

Table 2. Geophysical method, primary physical property and inferred properties.

Method	Primary Physical Property	Inferred Properties
Gravity	Density	Lithology, porosity
Seismic	Wave velocity, elastic moduli and density	Pressure, fluid saturation, porosity, stress field
Electrical	Electrical conductivity	Fluid type and saturation, chemistry
Electromagnetic	Magnetic permeability and electric permittivity	Fluid type and saturation, chemistry

Given multiple geophysical datasets collected with the same setup at different times, changes in the geophysical data between each collection can be associated with dynamic subsurface processes that are occurring over the period spanned by the acquisition efforts. This approach is known as time-lapse or 4D geophysics, and has been demonstrated to work for all geophysical methods listed in Table 2 for a wide range of applications (Day-Lewis et al., 2002, 2003; Versteeg and Johnson, 2008).

2.1.2 The Geophysical Signatures of Bioremediation

As noted in the introduction, enhanced bioremediation through injecting amendments is increasingly used to accelerate cleanup. A range of different amendments exists, all of which serve as nutrients for the microbial communities. Amendments include both water soluble amendments (such as lactate, ethanol and molasses) as well as slow release compounds (such as vegetable oil, HRC®, and mulch). It is not uncommon to inject thousands of gallons of amendment mixture per injection point.

The amendment mixture had an electrical conductivity that differed from the background electrical conductivity, and thus the injection of large amounts of amendment changed the subsurface bulk conductivity (which is a combination of the conductivity of the solid phase and liquid phase components).

2.2 PRIOR TECHNOLOGY DEVELOPMENT

The general concept and components of the HPMS system were developed in prior efforts by the project team. The components include:

- multi electrode electrical resistivity instruments and software to collect data
- multi electrode cables and electrodes
- software, middleware, and hardware for data transfer
- server based software for data ingestion, QA/QC and management
- inversion codes for the inversion of electrical geophysical data
- web interfaces allowing for result access by end users

The commercially available components developed previously and by others, were discussed in Section 2.1. The resistivity cables, acquisition unit, and electrodes used in this demonstration are commercial off the shelf components. While this demonstration used hardware from one vendor, multi-channel, multi electrode systems from multiple vendors could be used within a HPMS implementation.

2.3 TECHNOLOGY DEVELOPMENT CONDUCTED UNDER ESTCP PROJECT

This section details components for which substantial advances or extensions were made under ESTCP project ER-200717: (1) the time-elapse inversion resistivity code used and (2) the web based component for data processing and result delivery (Versteeg and Richardson, 2006). Both of these components have seen substantial enhancements after the completion of the technical part of ER-200717 in August of 2010.

2.3.1 Time-lapse Resistivity Inversion Code

An essential part of electrical geophysical monitoring is data processing. This data processing translates the field measurements into a subsurface bulk electrical conductivity distribution through a process called inversion. While this can be done analytically for simple models and small datasets, for all modern day datasets this is done through a numerical code. There are several commercially available electrical resistivity tomography (ERT) inversion codes, but each of these has limitations making them less than optimal for autonomous ERT monitoring.

To address these limitations, a new parallel 3D time-lapse (i.e., 4D) ERT inversion code was developed under funding support from the DOE (Johnson et al., 2010). This code was validated and tested against the data from the Brandywine site as described in Versteeg and Johnson, 2008, and has since been used in numerous characterization and monitoring applications at the Hanford site. This same code is currently being optimized for remedial applications in fractured rock under ESTCP project ER-201118. The code is built around the Message Passing Interface (MPI) standard (Gropp et al., 1996) allowing scalability on large distributed memory HPC systems. For instance, as of March 2012, the code has been successfully executed on two central processing units (CPU) for an inversion problem estimating several thousand bulk conductivity values, to over 3500 CPUs for a problem estimating over 1 million bulk conductivity values. For the Brandywine project, inversions were executed using 106 CPUs on a parallel computing system

housed at the Idaho National Laboratory. Such resources are commercially available in cloud computing environments such as the Amazon Elastic Compute Cloud (EC2) environment.

2.3.2 Web Applications for Data Processing and Result Delivery

During the demonstration, project incremental versions (adding increased functionality and robustness) of the HPMS code were used to provide monitoring capabilities. In the fall of 2010 the capability of the code at that time to provide real time monitoring was demonstrated live to DoD and DOE staff. Software code improvements made under the ESTCP project focused on the following three primary elements: 1) Middleware, software, and hardware—includes those components of the HPMS system which allow for the transfer of data collected in the field to a server, 2) Server based software—provides for data ingestion, QA/QC and management and, 3) Client side functionality software—provides a web site based interface to allow users to visualize data and results on demand.

2.4 EXPECTED APPLICATION OF TECHNOLOGY

This technology can be applied to monitoring of both environmentally and energy related processes. This technology is currently being applied by co=Principal Investigators (PI) Versteeg and Johnson to autonomously monitor rain infiltration at the Hanford 300 Area, and has been applied to monitor river-groundwater exchange, has been further developed under a DOE funded Phase I Small Business Innovation Research project. U.S. Geological Survey (USGS) PI's have adapted and extended the direct-push installation of electrodes for use at other sites, including the DOE Naturita and Hanford 300 Area sites. This work has greatly reduced installation cost and capital costs associated with instrumentation, as compared to the setup at Brandywine. As correct application and deployment of this technology does not require end users to manage or process geophysical data (they get direct access to changes in subsurface conductivity) it is well suited to monitor bioremediation amendments in the subsurface, and follow progress of remedial activities in general.

2.5 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The primary advantage of the technology demonstrated is the ability to provide volumetric, temporally dense information on amendment behavior to the site operator in near real time. Operators can track amendment movement in near real time and are able to link amendment injection histories to resulting amendment distributions. Alternative technologies rely on direct measurements in soil and groundwater. Because of the associated analysis time and cost, these alternative technologies do not provide a viable method to obtain similar information. This technology also has substantially lower recurring cost than direct sampling methods. In addition, while the HPMs system requires some upfront costs in terms of the resistivity system, the most expensive components of this system are reusable.

There are potentially four limitations to this method, including: 1) applicability in complex environments, 2) installation cost for resistivity wells, 3) spatial resolution and, 4) need for a sufficient contrast in electrical properties between amendment and initial bulk conductivity.

Applicability in complex environments: In extremely complex geologic and highly heterogeneous environments, the approach will be challenging to implement. For instance, even though this approach can be used in bedrock aquifers, there is an important limitation in that the geophysical signal is a function of changes to pore-fluids or at fluid-grain boundaries; hence it varies with porosity, and if the changing pore fluid occupies only a small fraction of the bulk (e.g., 2% porosity), the signal will be relatively weak. Another constraint is that electrical methods require good contact between electrodes and the soil, and if this is not possible (for instance if the soil is very dry) electrical methods will not provide good data.

Installation cost for resistivity wells: For the site discussed here, the project team used electrodes placed along boreholes using direct push technology in the first test. For the second test surface electrodes were used in addition to the borehole electrodes. The analysis includes a cost and performance comparison of surface against borehole electrodes. For extensive but shallow sites, or for fractured rock sites installation costs of borehole electrodes will be substantial and may make this technology non-cost competitive unless cheap ways to install vertical resistivity strings are developed. Several groups are working on such installation methods, which may include improved direct-push installation which could deploy many strings per day (rather than the ~3 wells/day rate done under this effort). Notably, our team has, since 2007, streamlined the hardware and installation approach to greatly reduce costs. For example, the USGS PI's have installed 9 direct-push wells instrumented with electrodes, thermistors, and sampling points (similar in capability to the Brandywine wells) at a DOE site in Naturita, Colorado, for a small fraction (~10%) of the cost of the Brandywine installation. This is discussed further in the cost analysis section.

Spatial resolution: The resolution of the inversion results degrades with the horizontal offset between wells relative to the vertical distance over which the imaging is performed. Thus, if high resolution is required this method may not provide it.

Need for a sufficient contrast in electrical properties between amendment and initial bulk conductivity: As discussed previously, this method depends on a sufficient contrast in electrical properties between the amendment and the ambient groundwater for its efficiency. Thus, for cases where such a contrast does not exist, the amendment would need to be "doped" with a substance that provides contrast; this could create complications or additional cost.

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3.0 PERFORMANCE OBJECTIVES

The performance objectives for this method as provided to the ESTCP office in the demonstration plan and are listed in Table 3, as well as whether these objectives were met.

Table 3. Performance objectives for effort.

Type of Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	3D Spatial resolution of amendment maps	Better than 1.5 meter	Yes
	Relative concentration gradients of amendments in 3D	Resolution in 15 % brackets	Yes
	Processing and delivery time of HPMS server	< 2 minutes	< 10 minutes[1]
	Temporal resolution of amendment maps	Better than 2 hours	Yes
Qualitative	Effectiveness of HPMS system in delivering actionable information to RPMs	Utilization of system by RPMs demonstrating use and application	Yes
	Ability to map geochemical parameters of interest	Demonstrated correlation between geochemistry and HPMS results	Yes

3.1 QUANTITATIVE PERFORMANCE CRITERIA

3.1.1 3D Spatial Resolution of Amendment Maps

The spatial resolution of amendment maps is given in meters. It is defined as the extent to which this method can resolve the exact spatial position of the amendment. This resolution can be calculated from independent knowledge of the position of the amendment. This information can be obtained both from knowledge on the injection location (as was done for both amendment injection efforts) or from sampling efforts (as was done for the first amendment injection). The 3D ERT inversions performed produced meshes of conductivity in between wells. Mesh element sizes varied in volume from 2.0e-4 m^3 near electrodes to 1 m^3 within the imaging zone. Element size is not equivalent to resolution (Day-Lewis et al., 2005), but is an upper bound. Geophysical tools (e.g., the resolution matrix) exist to evaluate resolution more quantitatively, but these are computationally intractable for large 3D problems. Based on modeling, resolution is estimated to be on the order of 1 meter, thus meeting the performance criteria.

3.1.2 Relative Concentration Gradients of Amendments in 3D

The relative concentration gradient of amendment injections is given in percent (%), where 100% is the highest concentration, and 0% is the background value. It can be calculated from the

[1] In the initial proposal the project team specified 2 minutes, but this period did not differentiate explicitly between the time when the raw data would be available (which is around 1 minute) and the time when the processed data are available (which depends on the size of the problem and the available computational resources, and was about 10 minutes in actuality). Here, this distinction is made. Data was successfully collected and made available in under the original 2-minute window, but is the time reported included processing, i.e., 10 minutes.

inverted resistivity datasets. This concentration gradient can be calculated independently from the sampling efforts.

3.1.3 Processing and Delivery Time of HPMS Server

The processing and delivery time of the HPMS server is defined as the wall clock time expired between the arrival of data on the server and the associated posting of results on the web interface. During this time, the following steps happen automatically:

1. Data arrival at the server triggers start of processing flow
2. Data is filtered using data QA/QC and common survey filters
3. Data is passed onto the inversion program
4. Parallel inverse code is executed
5. Result of inversion is included in output file for visualization
6. Results are visualized
7. Update is posted to website

The majority of the time in these steps (> 99%) is spent in step 4, the execution of the parallel inverse code. Most of the other steps take 1-5 seconds to execute. The inversion step wall clock time depends both on the number of nodes available to the inverse code, the size of the grid, and the number of data points to invert, as well as on the initial model. The fastest execution time is achieved if the number of nodes is the same as the number of electrodes, and if the starting model is relatively close to the final model. Note that there are several approaches used in time-lapse inversion. These range from (a) starting with a uniform half space every step (b) starting from the model obtained in the previous step, (c) starting with the model resulting from the inversion of the first dataset or (d) starting with some model which is an average of many models. Approaches (b-d) will require fewer iterations than approach (a).

The inversion implementation started with a model, which is the result of the inversion of the first (background) dataset. In this case a typical inversion can be performed in about 10 minutes, thus meeting the performance criteria.

3.1.4 Temporal Resolution of Amendment Maps

The temporal resolution is given as the time between each resistivity dataset. This temporal resolution is exactly the time it takes to collect each dataset. This time depends on the type of instrument used (single versus multi-channel), the total number of electrodes in the system, and the measurement schedule. The temporal resolution was on the order of 2 days for the Anaerobic BioChem (ABC®) injection which was monitored for one and a half years starting in March 2008 and was on the order of 25 minutes for the molasses injection.

3.2 QUALITATIVE PERFORMANCE CRITERIA

3.2.1 Effectiveness of HPMS System in Delivering Actionable Information to RPMs

The effectiveness of the HPMS in delivering actionable information to RPMs can be judged by (1) the form in which the HPMS provided information on amendment behavior, (2) the ease of

getting access to this information, and (3) the time elapsed between the amendment injection and when the information was available.

Form: The HPMS system provides information through an animation of spatial and temporal behavior of amendment behavior. This form makes it intuitively obvious to see where the amendment is going.

Ease of access: The HPMS system provides information through a standard web browser. No special software needs to be installed, and the information is available to any authorized user on demand.

Time elapsed: The time elapsed between data collection and information being available is in the range of tens of minutes to tens of hours (depending on several factors discussed previously). This is substantially faster than sampling based analysis results (which typically take weeks to months to become available.)

During the August 2010 molasses injection, the project's field team and guests to the site from DOE, DoD, and industry saw near real-time maps of amendment behavior as a molasses amendment was being injected. Actionable information was delivered to operators and decision makers in near real time.

3.2.2 Ability to Map Geochemical Parameters of Interest

The ability to map geochemical parameters of interest is based on relationships between the bulk electrical properties and those geochemical parameters. The derivation and validation of this relationship was demonstrated by providing a pre sampling estimate of anticipated sample results for the fall 2008 sampling effort to the DoD program manager. As discussed in sections 5 and 6 it was also demonstrated that the results were highly correlated with known geochemical processes on site, thus meeting the performance criteria.

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4.0 SITE DESCRIPTION

The Brandywine DRMO (USEPA, 2006) is an inactive DoD facility that occupies approximately eight acres of land. The U.S. Navy operated the site as a storage yard and marketing office from an unknown date until 1955, when it was transferred to the U.S. Air Force. In 1973, the Defense Supply Agency (DSA) assumed control of the site, and the Defense Property Disposal Organization received a permit from Andrews Air Force Base (AFB) to use the property. A remedial investigation was completed in 2005 (URS, 2005, 2006), and thus the site is well characterized. Based on historical evidence and the groundwater and soil data presented and discussed in the Brandywine Remedial Investigation (RI), the releases of Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)-regulated hazardous substances at the Brandywine DRMO resulted in three distinct plumes of dissolved chlorinated solvents in the groundwater.

4.1 SITE LOCATION

As shown in Figure 2, the Brandywine DRMO site is located in southern Prince George's County, Maryland, about 8 miles south-southeast of Andrews AFB. The site lies within the Potomac River Basin.

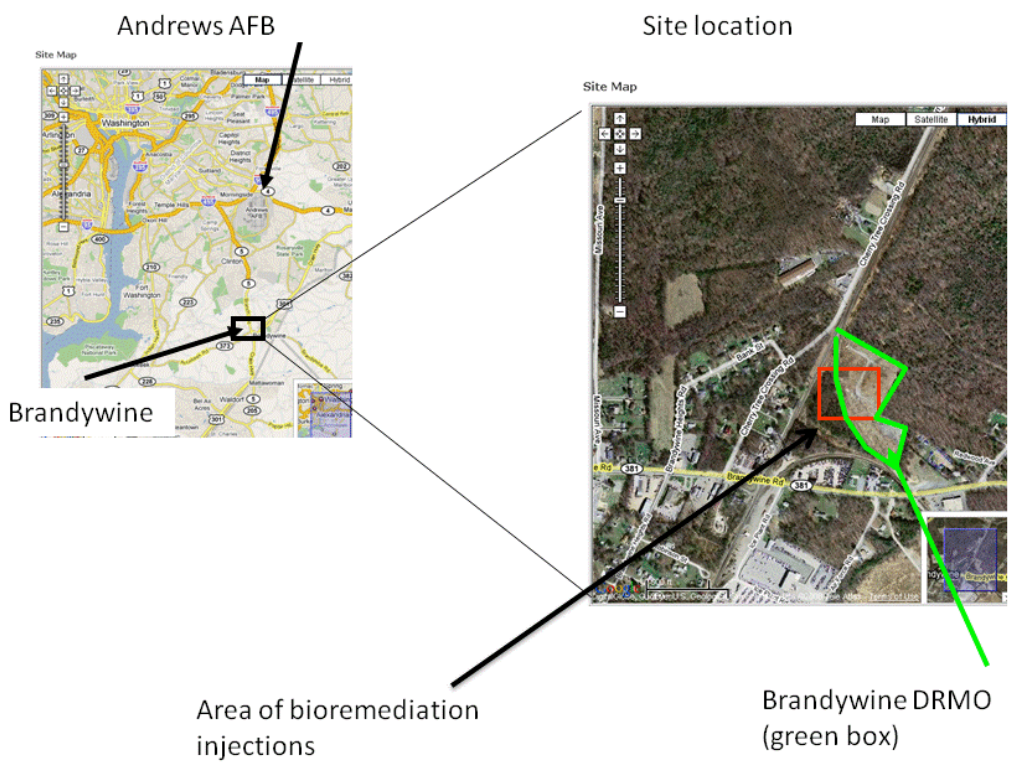

Figure 2. Site location of the Brandywine DRMO.

4.2 SITE GEOLOGY/HYDROLOGY

The site surficial materials consist of silt, silty-sand, and sand. Two formations are identified on the site: the Brandywine formation (about 0-30 feet [ft]) and the Calvert Formation (directly below the Brandywine formation) which behaves as an aquitard. Contamination is shallow, extending to about 30 ft below ground surface (bgs) in the Brandywine Formation. The target zone for remediation is bounded below by the Calvert Formation. The water table is near 5 ft bgs. Groundwater flow is toward the north, with a measured groundwater velocity of approximately 50 ft/year.

4.3 CONTAMINANT DISTRIBUTION

Based on historical evidence and the groundwater and soil data presented and discussed in the Brandywine RI, the releases of CERCLA-regulated hazardous substances at the Brandywine DRMO resulted in three distinct plumes of dissolved chlorinated solvents in the groundwater. The area of highest contaminant concentrations occurs west and northwest of the DRMO yard. The release or releases responsible for generating this plume most likely occurred near the northwest corner of the DRMO yard. A smaller, disconnected plume is located within the DRMO yard. There also is a smaller plume located to the northeast of the DRMO yard. The spill or spills responsible for groundwater contamination within the DRMO yard were events separate from the spills responsible for groundwater contamination northwest of the yard; the plumes are spatially disconnected. The plume within the DRMO yard is smaller and has lower concentrations of contaminants as is the smaller plume to the northeast. Figure 3 shows the plume within the DRMO yard and location of the ESTCP Dem/Val amendment injection points.

The most significant groundwater contaminants at the site, as defined by areal extent and concentrations above the MCLs for federal drinking water standards, are TCE, PCE, and cis-1,2-DCE. The maximum concentrations of TCE and PCE measured at the site are 224.2 milligrams per liter (mg/L) and 0.349 mg/L, respectively. The MCL for TCE and PCE is 0.005 mg/L. The maximum cis-1,2-DCE concentration measured at the site was 13.4 mg/L. The MCL for cis-1,2-DCE is 0.070 mg/L. The results of the site investigations indicate that the volatile organic compounds (VOC) in groundwater at the Brandywine site are present both as dissolved contaminants and as droplets or pools of DNAPL that contain primarily TCE.

Enhanced bioremediation amendment injections were conducted at over 1000 injection points within and bordering the plume. The injection point spacing was approximately 20 ft and multiple amendments and amendment concentrations were used.

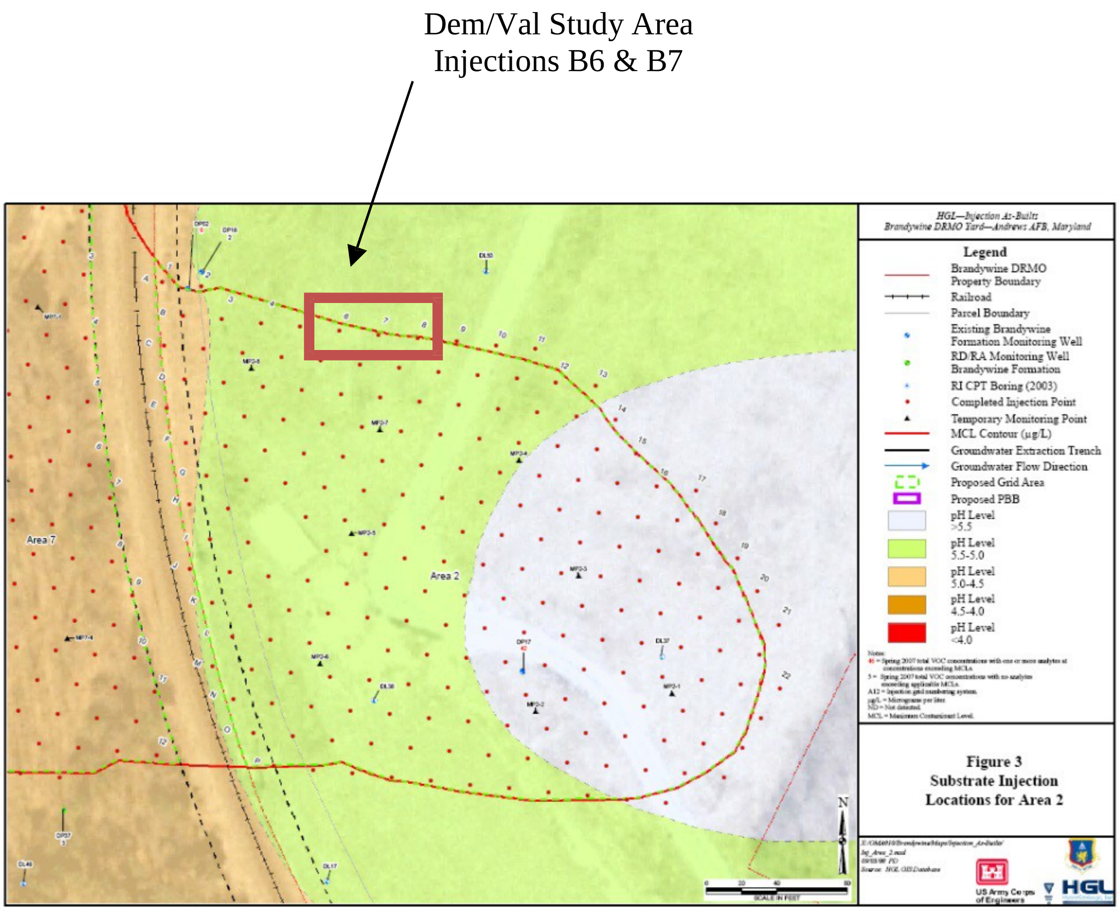

Figure 3. Layout of HPMS monitoring system overlain on general area of plume amendment injections.

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5.0 TEST DESIGN

5.1 EXPERIMENTAL DESIGN

The experimental design used to evaluate the performance objectives was driven by the constraints provided by the remedial effort described in the previous section (a bioremediation injection which was scheduled to occur in early spring of 2008). It was also driven by the site-specific remedial action at Brandywine, available infrastructure and the performance objectives. At the selected site, several hundreds of amendment injections were scheduled to take place. The project team's experimental design was formulated to take advantage of this by monitoring two of these injections. For this, electrodes and cables and the resistivity system were deployed. This required a semi-permanent housing for the hardware, access to line power, minimal sources of cultural noise (pipes, power lines, etc.). As the HPMS installation and associated infrastructure (e.g., shed, wells) should not interfere with the amendment emplacement efforts selected a location for the layout at the edge of the treatment area were selected. In addition to the site-design requirements associated with the geophysical data acquisition system, our experimental design also needed to consider collection of geochemical confirmatory data throughout the experimental plot. This required the emplacement of a sufficient number of sampling wells in our site. As a second line of geophysical evidence, our experimental plan included collection of crosshole radar data; thus our experimental design included installation of larger diameter (3-inch) wells to facilitate collection of radar data and borehole electromagnetic logs.

The initial experiment involved the monitoring of the injections of the propriety amendment ABC® performed as part of the site remedial effort. Based on feedback received from the ESTCP panel during an interim progress report in which the question arose to what extent our method would be applicable to other amendments, a second experiment was added which focused on the injection and short term monitoring of a second amendment. This experiment was performed in August 2010 and used molasses. The primary objective of the second experiment was to demonstrate (1) the applicability of the approach for a variety of amendments, including injections without pH adjustments, and (2) the ability of the HPMS system to provide near real-time monitoring information.

5.2 SITE LAYOUT

Based on the demonstration objectives, site layout, and remedial design, we emplaced sampling and resistivity wells surrounding injection points B6 and B7 were emplaced. The cables from the resistivity system were buried and run through a conduit into a small control shed which housed our electrical resistivity equipment. The spacing and geometry of the resistivity wells and the sampling points were driven by two factors: the expected behavior of the amendment in terms of movement, and the required spatial resolution of the electrical imaging. Previous work at the site indicated that the groundwater velocity at the site was approximately 60 ft/year (roughly from east to west). Initial plans called for monitoring the injection for about one to one and a half years, and our spacing was designed such that it would allow tracking of at least the easternmost amendment without it leaving the monitoring system area over the planned duration. A similar spacing was obtained from numerical modeling efforts. These agree with the rule of thumb that horizontal spacing should ideally be about 50-70% of vertical array length.

Injections of ABC® occured at well B6 on March 7, 2008, and in well B7 on March 10, 2008. Injections of 40% molasses occured in the same wells in August 2010.

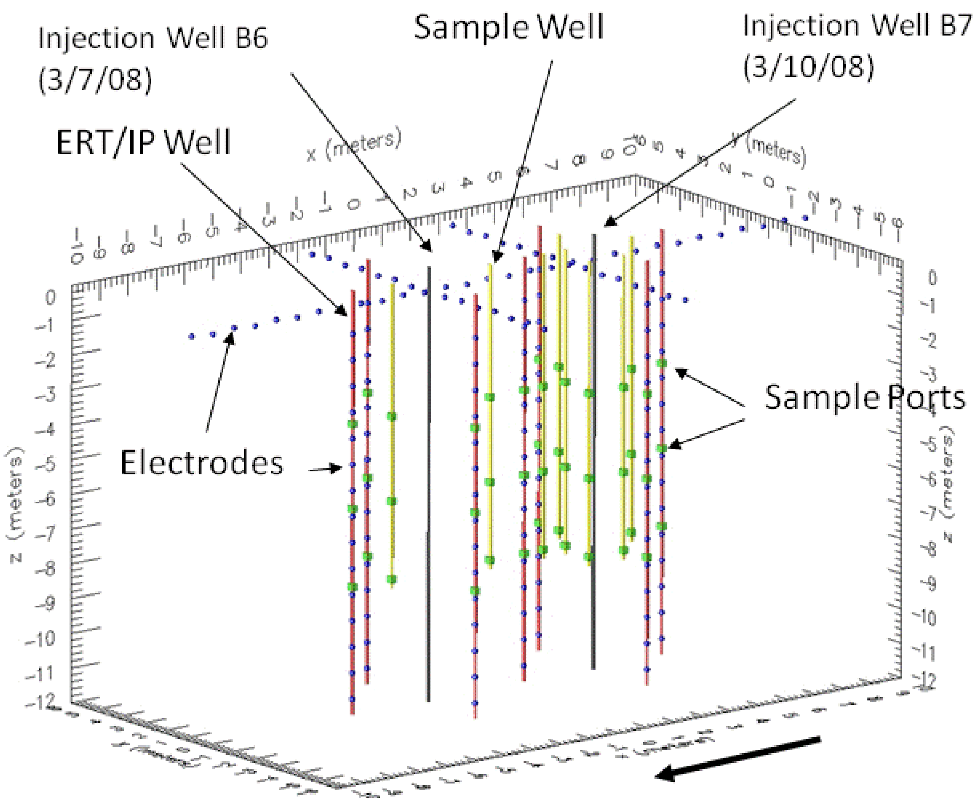

Figure 4. Site detail showing relationship between borehole wells and sample wells.
Locations of two injections for long-term monitoring experiment are shown. Layout of monitoring system in general area of injections (lower left). The system consists of 7 ERT boreholes and three surface cables and 8 dedicated sampling wells. These were deployed around two of the sampling points (B6 and B7). Note that for the second injection in August 2010 additional surface cables were used. Each red dot on the lower left figure represents an amendment injection location.

5.3 MEASUREMENTS

Measurements included initial characterization during well installation (measurements collected during direct push installation), pre injection measurements (cross hole ground penetrating radar [GPR], pre-injection resistivity and well sampling data) and post injection measurements (time lapse resistivity, and well sampling). Electrical resistivity measurements were taken from March 2008 through September 2010. Chemical sampling occurred periodically (Table 4), with some sampling events focused on field parameters (fluid conductivity, pH) and others focused on laboratory analysis for ions and organics. In addition, site wide sampling results were obtained from HydroGeoLogic, Inc. and Andrews AFB which provided site wide monitoring of subsurface conditions. These show low methane, a slight increase in iron and manganese slow fermentation in October 2008 and January 2009, significant development of reducing conditions in April 2009, as well as high methane reduction, low dissolved oxygen, and oxidation reduction potential.

Table 4. Overview of sampling events performed by project team.

Groundwater sampling events

Injection of 7% ABC (ethyl lactate + fatty acids) + 200mM $NaHCO_3$

	March 2008 (pre-inject) subset	March (post-inject) Subset	April 2008 All wells	August 2008 All wells	July 2009 All wells	April 2010 All wells
pH	X	X	X	X	X	X
Fluid conductivity	X	X	X	X	X	X
Anions	X	X		X	X	
Cations	X	X		X	X	
Organic Acids	X	X		X	X	
VOC	X	X			X	
TOC	X	X		X	X	
Fe^{2+}	X	X			X	
Dissolved O_2	X	X		X	X	
Sulfide	X	X		X	X	

5.4 RESULTS AND INTERPRETATION

Time-lapse ERT data were processed every other day to provide 3D snapshots of the change in bulk conductivity from pre-injection conditions. Figure 5 shows a subset of the ERT results. Figure 6 shows a comparison of bulk resistivity and measured fluid conductivity.

Our interpretation of the long-term monitoring dataset for the ABC® amendment is as follows: During the first year the amendment slowly moved downward (likely from density-driven flow) to spread over the lower confining unit moving in the direction of groundwater flow. During this period, bulk conductivity decreased as the emplaced amendment plume underwent dilution and dispersion. During the second year a significant increase in bulk conductivity was observed in the ERT results, which corresponded to the onset of biological activity as observed by the contractor sampling data. Our interpretation of this is the following. Between March 2008 and January 2009 there is little microbial activity. The rise and fall in bulk conductivity is due to changes in fluid conductivity, which is caused by groundwater flow driven migration of the amendment.Between January 2009 and April 2010 the geochemical data suggest vigorous microbial activity. The coupled decrease in fluid conductivity and increase in bulk conductivity cannot be explained by changes in fluid chemistry, suggesting an increase in interfacial conductivity (possibly iron-sulfide precipitation). This is in agreement with the decreasing correlation between fluid conductivity and bulk conductivity. Most activity occurs just above confining unit (corresponding to amendment distribution).

The findings indicate that geophysical monitoring of bioremediation can be used both to map the initial emplacement and movement of the amendment as well as the actual occurrence of bioremediation. Note that monitoring bioremediation itself went beyond the goal of the project, which focused on monitoring amendment emplacement.

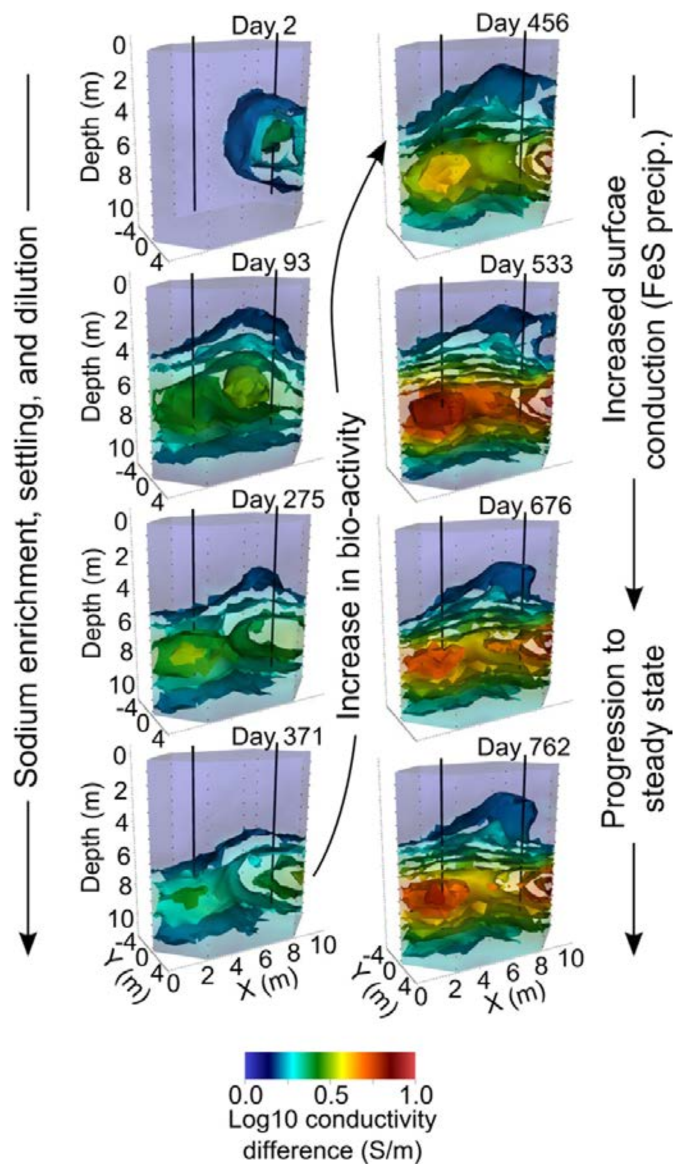

Figure 5. 3D time-lapse ERT monitoring results up to 762 days after the March 2008 injection.

Injection intervals are shown as black vertical lines. Bulk electrical conductivity differences are shown as isosurfaces. The left column shows the amendment sinking, spreading, and diluting over the lower confining unit during the first year. In the second year, a significant increase in bulk conductivity corresponds to the onset of biological activity as confirmed through sampling efforts. Increases in bulk conductivity during this period are likely caused by iron sulfide precipitation.

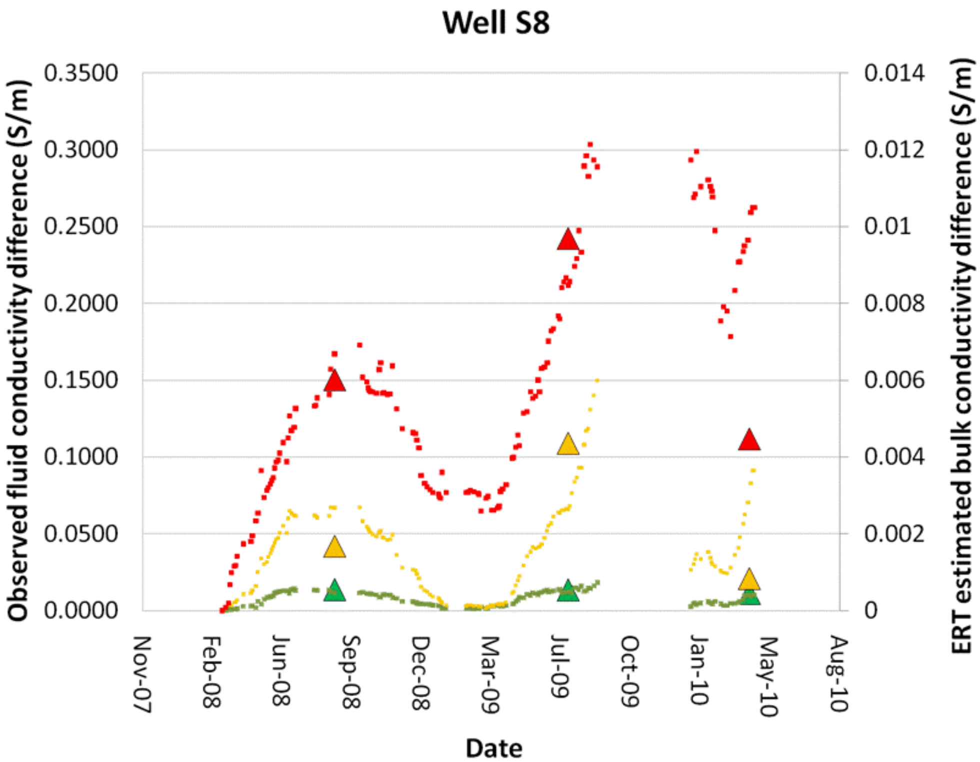

Figure 6. Comparison of ERT estimated conductivity against fluid measured conductivity.

Dots are ERT inversion results. Triangles represent measurement at well ports. Green - 10 ft bgs, yellow - 18 ft bgs, red - 25 ft bgs.

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6.0 PERFORMANCE ASSESSMENT

The performance objectives for our method as provided to the ESTCP office in the demonstration plan are provided in Table 5. All of these performance parameters were met. The following sections discuss the assessment of these performance parameters.

Table 5. Performance objectives.

Type of Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	3D Spatial resolution of amendment maps	Better than 1.5 meters	Yes
	Relative concentration gradients of amendments in 3D	Resolution in 15 % brackets	Yes
	Processing and delivery time of HPMS server	< 2 minutes	< 10 minutes[2]
	Temporal resolution of amendment maps	Better than 2 hours	Yes
Qualitative	Effectiveness of HPMS system in delivering actionable information to RPMs	Utilization of system by RPMs demonstrating use and application	Yes
	Ability to map geochemical parameters of interest	Demonstrated correlation and between geochemistry and HPMS results	Yes

6.1 QUANTITATIVE PERFORMANCE CRITERIA

6.1.1 3D Spatial Resolution of Amendment Maps

The spatial resolution of electrical conductivity amendment maps is given in meters. It is defined as the extent to which the HPMS method can resolve the exact spatial position of the amendment. This resolution was calculated from independent knowledge of the position of the amendment, both in the initial long term ABC® amendment injection and the molasses amendment injection. For both of these the emplacement location of the amendment was known and can be compared to the location of the amendment as provided by the electrical resistivity inversion. This comparison showed that the spatial resolution is better than 1.5 meters, and possibly as good as 0.5 meters. **This performance criteria was met.**

[2] In the initial proposal the project team specified 2 minutes, but this period did not differentiate explicitly between the time when the raw data would be available (which is around 1 minute) and the time when the processed data are available (which depends on the size of the problem and the available computational resources, and was about 10 minutes in actuality). Here, this distinction is made. Data was successfully collected and made available in under the original 2-minute window, but is the time reported included processing, i.e., 10 minutes.

6.1.2 Relative Concentration Gradients of Amendments in 3D

The calibration demonstration showed that values of electrical conductivity, values of fluid conductivity, and total organic acids for the first part of the amendment injection effort. This allows us to provide relative concentration gradients of amendments in 4D. **This performance criteria was met.**

6.1.3 Processing and Delivery Time of HPMS Server

The processing and delivery time of the HPMS server is defined as the wall clock time expired between the arrival of data on the server and the associated posting of results on the web interface. During this time, the following steps happen automatically:

1. Data arrival at the server triggers start of processing flow
2. Data is filtered using data QA/QC and common survey filters
3. Data is passed onto the inversion program
4. Parallel inverse code is executed
5. Result of inversion is included in output file for visualization
6. Results are visualized
7. Update is posted to website

The majority of the time in these steps (> 99%) is spent in step 4, the execution of the parallel inverse code. Most of the other steps take 1-5 seconds to execute. The inversion step wall clock time depends on the number of nodes that the inverse code can use, the size of the grid, and the number of data points to invert, as well as on the initial model. The fastest execution time is achieved if the number of nodes is the same as the number of electrodes, and if the starting model is relatively close to the final model.

The approach used here started with a model, which is the result of the inversion of the first (background) dataset. For the molasses experiment (where the performance of our system was formally timed) a typical inversion was performed in about 10 minutes, thus meeting performance criteria. Note that improvements in the underlying code as well as improvements in computational hardware will further reduce this time. **This performance criteria was met.**

6.1.4 Temporal Resolution of Amendment Maps

The temporal resolution is given as the time between each resistivity dataset. This temporal resolution is exactly the time it takes to collect each dataset. This time depends on the type of instrument used (single versus multi-channel), the total number of electrodes in the system, and the measurement schedule. The temporal resolution was on the order of two days for the ABC® injection which was monitored for one and a half years starting in March 2008. For the molasses injection, the time for each data acquisition run was 28 minutes. Once the data acquisition was completed data transfer, processing and visualization added another ten minutes such that data was available to the end user within 40 minutes of the start of data acquisition **The temporal resolution performance criteria was met.**

6.2 QUALITATIVE PERFORMANCE CRITERIA

6.2.1 Effectiveness of HPMS System in Delivering Actionable Information to RPMs

The effectiveness of the HPMS in delivering actionable information to RPMs was judged by (1) the form in which the HPMS provided information on amendment behavior, (2) on the ease of getting access to this information, and (3) on the time elapsed between when the amendment injection and when the information was available.

- ***Form:*** The HPMS system provides information through an animation of spatial and temporal behavior of amendment behavior. This form makes it intuitively obvious to see where amendment is going;
- ***Ease of access:*** The system provides information through a standard web browser. No special software needs to be installed, and the information is available to any authorized user on demand.
- ***Time elapsed:*** The time elapsed between data collection and information being available is in the range of tens of minutes to tens of hours (depending on several factors discussed previously). This is substantially faster than sampling based analysis results (which typically take weeks to months to become available.)

A specific example of the effectiveness of the HPMS system was provided during the August 2010 molasses injection. At that time the field team and guests to the site from DOE, DoD and industry, saw near-real time maps of amendment behavior as molasses was being injected. Actionable information was thus being delivered to operators and decision makers. **This performance criteria was judged to be met.**

6.2.2 Ability to Map Geochemical Parameters of Interest

The ability to map geochemical parameters of interest is based on relationships between the bulk electrical properties and those geochemical parameters. The ability of the HPMS to map and predict these parameters was demonstrated by providing a pre-sampling estimate of anticipated sample results for the Fall 2008 sampling effort to the DoD program manager. It was also demonstrated that our results are highly correlated with known geochemical processes on site, thus meeting our performance criteria. **This performance criteria was judged to be met.**

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7.0 COST ASSESSMENT

7.1 COST MODEL

The cost model for the Brandywine demonstration/evaluation is provided in Table 6. This model reflects startup, sampling, operational, and demobilization costs associated with the HPMS and its demonstration/evaluation. The model, intended for use as a tool in costing adoption of a HPMS, does not reflect project expenditures related to development of software or research and development of components of the HPMS. Nor does the model reflect potential cost savings compared to the Brandywine project resulting from ongoing development of installation procedures, as discussed in the next section.

Table 6. Cost model for an HPMS similar to the Brandywine demonstration.

Cost Element	Data Tracked During the Demonstration	Costs (gross)	
Startup costs	• Drilling (19 wells) • Resistivity control-unit • Resistivity cables (7 wells, 4 surface cables) • Labor (total of 160 hours assumed, with travel and per diem) for two people – approximated • Labor (160 hours assumed) for survey geometry design and setup of database and server communications	Drilling	$40K
		Resistivity control unit	$80K
		Resistivity cables	$11K
		Labor and travel for fieldwork	$22K
		Labor for design	$16K
Operational costs	• 1-day site visit by one technician with salary, 1-day travel and per diem, once per quarter, for one year – approximated and site dependent • Electricity – not tracked • Labor for processing, inversion, interpretation – 80 hours per year, senior scientist	Labor and travel for field visit	$4K
		Electricity	$360
		Labor for processing	$9K
Sampling	• 4 sampling events, water-quality field parameters, major ions, contaminants with 2-day site visit by two scientists each time	Labor and travel	$24K
		Lab analysis	$76K
Demobilization	• Well abandonment (19 wells) by certified driller • Disposal of materials • Two scientists, labor and travel, 3 days	Driller	$7.5K
		Waste disposal	$4K
		Labor and travel	$8K

7.2 COST DRIVERS

Important cost drivers affecting the application of the HPMS include the 1) scale of heterogeneity at the site, which dictates well offsets for the HPMS, 2) ease of drilling (e.g., suitability of direct-push, rock vs. unconsolidated material, etc.), and 3) on-site access to power and means of data transfer (e.g., availability of internet connection). Drivers 1-2 also are important for conventional monitoring efforts. For example, drilling costs affect conventional sampling even more than HPMS, which minimizes the need for boreholes. A short scale of heterogeneity would limit distance between observation wells even more than the distance between HPMS wells. Thus, the driver unique to the HPMS is the third, i.e., access to on-site power and means of data transfer. Without these, most applications of the HPMS would be cost-

prohibitive, as frequent site visits would be required. Furthermore, the primary advantages of the HPMS—autonomous, automated and real-time monitoring—would not be realized.

7.3 COST ANALYSIS

Cost savings associated with deployment of a HPMS can be derived from any or all three of these mechanisms: 1) accelerated time to remediation and site closure and/or reduction of amendment injections resulting from improved delivery of amendments, 2) decreased frequency of sampling resulting from limited sampling events based on when changes are observed in geophysical monitoring results and/or, 3) decreased number of samples collected resulting from use of geophysical results to fill in gaps spatially between sampling points.

The project team envisions several different scenarios under which the HPMS would be useful, these ranging from monitoring at a single injection point for verifying general injection design to monitoring site-wide for verifying amendment extent spatially. The project Final Report presents the following three separate cost-analysis scenarios to quantify potential savings associated with deployment of a HPMS for different purposes and scales of remedial action:

1. A minimal HPMS system designed to monitor a single injection point;
2. Site-scale HPMS system, designed to monitor 20 separate injection points spread across a large site; and
3. Site-scale HPMS system, designed to monitor a 100-meter by 100-meter side, with spatial coverage site-wide.

The highest cost savings are achieved with Scenario 2 and this cost model and analysis is provided in Section 7.3.1 of the Cost and Performance Report. End users having applications more closely matching scenarios 1 or 3 are referred to the project Final Report.

Whereas the Brandywine cost model (Table 6) reflects deployment costs of a HPMS based on our stage of research and development in 2007, the analyses presented here reflect potential deployment costs for a HPMS today, and thus reflect cost savings resulting from research and development under the ESTCP project and related ongoing grants. For example, co-PI's at the USGS have developed a low-cost alternative to the electrode/sampling setups installed in direct-push wells at Brandywine. These new setups do not rely on a polyvinyl chloride (PVC) backbone or commercially fabricated resistivity cables; rather they use collapsible fiberglass backbones and stainless-steel adhesive-backed tape for electrodes. This design facilitates significant cost savings in shipping and installation. The fiberglass setups also decrease material costs associated with electrode/sampling setups from approximately $2000 to $100. The new design has been used successfully by the USGS under two grants funded by the DOE's Subsurface Biogeochemical Research program to study radionuclide-contaminated DOE sites in Naturita, Colorado, and Hanford, Washington. In developing Table 7 use of the most cost-effective, state-of-the-art components is assumed.

7.3.1 Cost Analysis Scenario 2: Site-Scale Monitoring at 10 Locations

The cost analysis presented in Table 7 is based on a project in which the objectives for the HPMS are focused on verification of amendment emplacement at multiple injection points, as required at a site with substantial heterogeneity. Here, it is assumed the HPMS would be used for monitoring for three years of a longer remediation action, with sampling for calibration/validation (i.e., two sampling events) only in year one and subsequent use of that calibration for prediction in years two and three. Our reference for comparison is based on three years of conventional sampling at quarterly frequency for two years and then one more event in year three (i.e., a switch to annual frequency). A site similar to Brandywine in terms of the depth of the target zone (~30 ft) with similar drilling costs were used for the cost model. Use of four electrode/sampling installations at 10 locations for the HPMS. The reference costs are based on conventional sampling at four wells per injection location; hence the reference case for conventional sampling involves the same drilling costs, for the same number of sampling points. This scenario therefore aims at quantifying the cost-benefit of geophysical enhancing a conventional monitoring network. The HPMS provides more information, in space and time, than conventional sampling, although the quality of this information depends in years two and three on the strength of the relation between the geophysical results and amendment concentration, as identified in the calibration/validation step. In this scenario, the cost of the resistivity control unit is not discounted, which would be fully dedicated to the site. 100% of its cost is included in the analysis.

As shown in Table 7, the HPMS for this three-year scenario costs $537K compared to $1180K for conventional sampling to provide less information (in space and time) but using the same number of sampling points and drilling budget as the geophysically enhanced HPMS. Thus the HPMS achieves a ~55% cost savings while providing more information. These savings do not include additional possible savings resulting from access to real-time information to improve decision making or optimize procedures in the field.

The incremental costs of the HPMS are concentrated in the first years of monitoring, in the capital costs for startup. The cost analysis presented in Table 7 would be more favorable toward the HPMS if a longer time horizon were considered. If it is assumed that the calibration is re-established on a five-year interval and sampling for the conventional design is annually after year two, cost savings for a remediation monitoring effort would continue to increase for the life of the HPMS, reaching $2.3M in 30 years. Note that this simple comparison does not account for inflation.

Table 7. Cost analysis for HPMS Scenario 2 (30 year costs).

<table>
<tr><th colspan="4">HPMS Costs</th></tr>
<tr><th>Cost Element</th><th>Sub elements</th><th colspan="2">Costs (gross)</th></tr>
<tr><td rowspan="5">Startup costs</td><td rowspan="5">• Drilling (40 ERT/sampling wells)
• Resistivity control-unit
• Resistivity setups (40 wells)
• Labor (total of 80 hours assumed, with travel and per diem) for two people – approximated to set up connections
• Labor (40 hours assumed) for survey geometry design and setup of database and server communications</td><td>Drilling</td><td>$80K</td></tr>
<tr><td>Resistivity control unit with additional multiplexers (dedicated)</td><td>$120K</td></tr>
<tr><td>Resistivity cables</td><td>$8K</td></tr>
<tr><td>Labor and travel for fieldwork</td><td>$20K</td></tr>
<tr><td>Labor for design</td><td>$4K</td></tr>
<tr><td rowspan="3">Operational costs</td><td rowspan="3">• 2-day site visit by one technician with salary, 1-day travel and per diem, twice – approximated and site dependent
• Electricity – 3 years
• Labor for processing, inversion, interpretation – 80 hours per year, senior scientist</td><td>Labor and travel for field visit</td><td>$8K</td></tr>
<tr><td>Electricity</td><td>$720</td></tr>
<tr><td>Labor for processing</td><td>$24K</td></tr>
<tr><td rowspan="2">Sampling</td><td rowspan="2">• 2 sampling events in first year, 40 wells, water-quality field parameters, major ions, contaminants with 5-day site visit by 4 scientists each time</td><td>Labor and travel</td><td>$60K</td></tr>
<tr><td>Lab analysis</td><td>$180K</td></tr>
<tr><td rowspan="3">Demobilization</td><td rowspan="3">• Well abandonment (40 wells) by certified driller
• Disposal of materials
• Two scientists, labor and travel, 4 days</td><td>Driller</td><td>$10K</td></tr>
<tr><td>Waste disposal</td><td>$10K</td></tr>
<tr><td>Labor and travel</td><td>$12K</td></tr>
<tr><td colspan="3">TOTAL (not including reusable hardware)</td><td>$537K</td></tr>
<tr><th colspan="4">Conventional Sampling Comparison</th></tr>
<tr><td>Startup costs</td><td>• Drilling (40 sampling wells)</td><td>Drilling</td><td>$80K</td></tr>
<tr><td rowspan="2">Sampling</td><td rowspan="2">• 9 sampling events over 3 years - water-quality field parameters, major ions, contaminants with 5-day site visit by four scientists each time</td><td>Labor and travel</td><td>$270K</td></tr>
<tr><td>Lab analysis</td><td>$810K</td></tr>
<tr><td rowspan="2">Demobilization</td><td rowspan="2">• Well abandonment (40 wells) by certified driller
• Disposal of materials</td><td>Driller</td><td>$10K</td></tr>
<tr><td>Waste disposal</td><td>$10K</td></tr>
<tr><td colspan="3">TOTAL</td><td>$1180K</td></tr>
</table>

8.0 IMPLEMENTATION ISSUES

8.1 DEPLOYMENT

The HPMS system requires the installation of vertical arrays of electrodes and/or surface electrodes, as well as the deployment of electrical geophysical data acquisition hardware and supporting infrastructure (i.e., power infrastructure, wireless data transmission capabilities, hardware enclosures). An example of deployment cost for system data acquisition hardware, electrodes, electrode geometry, and typical mix of surface and borehole electrodes is provided in Section 7.3 Cost Analysis. This configuration can be scaled to fit site specific requirements.

The most variable cost is that of electrode installation, especially if that is done in boreholes. Whereas surface electrode installation is fairly straightforward and low cost (for example, the installation of the two surface cables for the molasses monitoring were done in one day by one person), installation of borehole electrodes can be very costly.

Until recently, the installation of borehole resistivity arrays was done by the installation of electrodes either in fully screened PVC boreholes or connected to the side of PVC or fiberglass rods. This method is time consuming and costly. To address this problem, several project PI's have leveraged experience from the Brandywine Demonstration/Validation to design much lower-cost, smaller diameter electrode/sampling setups that do not require setting casings and which can be fabricated off-site; these fold up, facilitating shipping to remote sites. With these modifications, the estimated hardware cost for each electrode string is reduced by 90%, and direct-push installation can be performed with smaller diameter drill rod and thus performed more rapidly.

Surface electrodes and cables can be repurposed, whereas borehole electrode arrays are commonly abandoned or destroyed during removal. If borehole electrodes were emplaced in heavily contaminated soil, removal and decontamination costs may exceed replacement costs.

8.2 OPERATIONAL ENVIRONMENT ISSUES

Operation of the HPMS system typically requires some kind of enclosed and protected space to house the resistivity instrument, power supplies for the resistivity instrument and a field computer. A field trailer or small shed will generally suffice. A standard 15 Amp, 120 volt power circuit will typically be sufficient to operate the system. A standard problem which is encountered in the field is that small enclosures tend to experience large temperature fluctuations during the year. While both the resistivity equipment and computers typically can deal with low temperatures found in winter, extreme heat has led to equipment failures. Thus, some kind of basic climate control (heat in the winter, air conditioning in the summer) is often recommended. In the Demonstration/Validation effort several issues with reliable power at the site were encountered. Power interruptions shut down the system, and current resistivity hardware requires a manual reboot of the control computer for resumption of data acquisition. Reliable power is a requirement for system operation.

8.3 REGULATORY ISSUES

In general, if installed correctly the geophysical wells will not provide contaminant conduits. The material involved in the electrode arrays is relatively benign (stainless steel for the electrodes and PVC jacketed copper cable for the cabling) and not expected to be a contaminant source. Thus, the only permits/regulations would be those which would normally apply to environmental restoration site well installations.

The only requirement for accessing the results of the HPMS system is a web browser. However, as the information generated by HPMS is potentially sensitive, controls will be put in place whereby access to information and data is tied to user/passwords and different levels of access to data. Such a control would implement standard official use only restrictions.

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APPENDIX A

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